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# On licensing and diffusion of clean technologies in oligopoly*

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**Abstract**

Clean technologies implemented by polluters subject to environmental regulation are often developed and patented by specialized technology suppliers. This paper investigates the impact of the environmental regulation stringency on the diffusion of patented clean technologies when the polluters (i.e. *the potential licensees*) compete in imperfectly competitive markets. We show that the polluters' willingness to pay for clean technology and the diffusion of such technology (i.e. the extent to which it is privately disseminated through licensing) depend not only on the regulatory stringency and the technological efficiency, but also on the polluters' competitive environments. More stringent regulations (e.g., higher carbon taxes) or increased technological efficiency (e.g., supported by more R&D subsidies) do not necessarily induce more diffusion of efficient clean technologies. Indeed, as the returns to implementing a clean technology increase, so do the technology supplier's incentives to sell fewer licenses so as to extract more rent from each of its licensees.

**Key Words:** *Clean technology, Environmental Regulation, Oligopoly, Licensing*

***JEL*** **Classifications:** $Q55, Q58, L22$

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# 1 Introduction

Pollution is a pervasive byproduct of firms' activities in many highly concentrated industries. For example, emissions of air pollutants or greenhouse gases like carbon dioxide ($CO_2$) are characteristic of industries such as chemicals, cement, pulp, petroleum and electricity generation to name a few. To cope with that, governments increasingly rely on environmental policies such as emissions taxes or permits trading systems.[1] By increasing the perceived costs of implementing polluting technologies, such policies provide polluters with incentives to implement environmentally sounder production processes and are thus expected to foster the development and the diffusion of clean technologies.

Empirical evidence however suggest that several important environmental policies have, thus far, failed to induce the expected pace of environmental innovation. The leniency of these regulations is often put forth as the main explanation of such failure, and tighter regulations are often considered a must to encourage the needed investments.[2] Also, the *relative* inefficiency of available cleaner alternatives to conventional technologies is another factor hampering their diffusion. Conventional wisdom thus suggests that more stringent regulations (e.g., those stemming from lower emissions caps) will *necessarily* induce more widespread diffusion of clean technologies. Likewise, the development of more efficient clean technologies (e.g., as a result of increased R&D subsidies) should facilitate their diffusion.

Arguably, too low carbon prices do not provide adequate incentives to replace cost-effective (but dirty) technologies by less efficient, low-carbon technologies.[3] However, many clean technologies implemented by polluters subject to environmental regulation are developed in patented by private technology suppliers.[4] The latter's incentives to develop and disseminate these technologies are determined by the prospects of licensing revenues, that is, by the polluters' *induced* willingness to pay for such technologies.

This paper investigates the impact of the stringency of environmental regulation on *diffusion* of patented clean technologies when *the potential licensees* (i.e. the polluters) compete in an imperfectly competitive product market. Our contribution to the environmental economics

[1] Leading examples include the US cap-and-trade program for sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) as well as the European Union multi-sector emissions trading scheme (EU-ETS) covering $CO_2$ emissions from all the industries cited above.

[2] For example, the lax emissions caps of the EU-ETS and the US Regional Greenhouse Gases Initiative (RGGI), which have resulted in low allowances prices, are held responsible for the weak impact that these regulations have had on environmental innovation.

[3] In 2012, the unit price of EU Allowances reached a level as low as 6 euros, while RGGI auction cleared at a minimum price of $1.93 per $CO_2$ allowance.

[4] The clean technology industry is often referred to as the eco-industry. See e.g., David and Sinclair-Desgagné (2005).

literature is twofold. Firstly, we consider *process innovations* reducing emissions *ex ante* by modifying the polluters' production processes. In contrast, most of the literature on induced innovation focuses on end-of-pipe abatement technologies (i.e., reducing emissions *ex post*). Then, while most of the literature assumes away strategic interactions in the polluters' output market (typically by assuming perfect competition in this market) and/or *presumes* that environmental innovation reduces the costs of complying with environmental regulation, we *derive* the resulting environmental compliance costs *in oligopoly*.[5] Incorporating the more realistic feature of imperfect competition allows us to emphasize how strategic interactions among polluters might influence their individual decisions regarding environmental investments.

Secondly, we examine how the incentives of profit-maximizing technology suppliers to disseminate patented clean technologies are influenced by those strategic considerations. We argue that the difference between the profit realized during the compliance period by a polluter implementing a patented clean technology (hereafter *a licensee*) and that realized by a dirtier competitor using conventional technology might well exceed the mere compliance cost savings identified with a polluter's willingness to pay for environmental innovation, as seen in previous literature (see e.g., Milliman and Prince (1989), Fischer et al. (2003) among others). We therefore refer to this difference as the *environmental rent* arising from technological innovation. Naturally, part of the rent accruing to each licensee (which provides an upper bound of the polluters' individual willingness) to pay for the patented clean technology returns to the technology supplier through the proceeds of licensing.

In our model, the patented clean technology is licensed by a single technology supplier to polluters competing à la Cournot in a polluting oligopolistic industry subject to an emissions tax regulation. We assume throughout the paper that the regulation stringency (i.e. the tax rate) is set *once and for all* prior to the beginning of the compliance period and before the polluters' adoption decisions. In so doing we abstract away from potential time-inconsistency or commitment problems policy-makers could face.[6] Nevertheless, such a modeling choice is motivated by the practical prevalence of that kind of *ex ante* commitment in existing regulations.[7]

Intuitively, the more stringent the environmental regulation is, the more each polluter should be willing to pay for a *given* clean technology. Likewise, the more efficient a patented clean technology is, the more each polluter should be eager to acquire a license to use it. We show, however, that *given the regulation stringency*, a polluter's willingness to pay for a given clean

[5]See e.g., Downing and White (1986), Fischer et al. (2003), Milliman and Prince (1989), Requate and Unold (2003), Requate (2005b).

[6]See e.g Laffont and Tirole (1996), Requate (2005b) or Montero (2011) on this issue.

[7]The importance to providing investor with long-term visibility has led regulators to commit to stick to a policy for several year-compliance periods.

technology might depend on strategic interactions in the ensuing product market competition stage. Focusing on simple licensing contracts such as fixed license fees (or equivalent basic auction mechanisms), we find the following interesting results. When polluters produce strategic substitutes, more stringent regulations *do not necessarily* induce more diffusion of efficient clean technologies. Likewise, increased technological efficiency (e.g., supported by R&D subsidies) does not necessarily lead to more licensing of clean technologies.

The reason behind these counter-intuitive results is the following. When licensing a patented clean technology, the technology supplier (which, by definition, is endowed with some monopoly power over the patented clean technology) trades off two countervailing effects. On the one hand, selling an extra license at a given price increases revenue (*the revenue effect*), but on the other hand, each licensee imposes a negative externality on its competitors (reduced profits) and thus reduces every polluter's willingness to pay for a license (*the rent dissipation effect*).

While the revenue effect encourages more licensing, the rent dissipation effect induces the technology supplier to restrict the dissemination of its technology by pursuing a harsh licensing strategy. The stricter the environmental regulation or the more efficient the patented technology, the stronger is the rent dissipation effect. Thus, as the perceived cost of polluting increases (as a consequence of more stringent regulations), or as the technology efficiency improves (e.g., as a result of increased R&D subsidies), so do the technology supplier's incentives to sell fewer licenses so as to extract more rents from each of its licensees. For instance, by charging higher licensing fees, the technology supplier will discourage more polluters from adopting its patented clean technology.

On welfare grounds, the diffusion of clean technologies is desirable only to the extent that the (sunk) adoption costs incurred by the polluters do not exceed the social benefits arising from environmental innovation.[8] Throughout, we implicitly maintain the assumption that, apart from the licensing fees, there are no significant costs to adopt the patented clean technology.[9] Ultimately, however, whether *rationing*, that is, precluding some polluters from implementing its clean technology is a privately optimal from the technology supplier's point of view depends on the polluting industry's structural parameters (e.g., number of firms, demand elasticity, *et cetera*).

It is important to stress that our message is neither that laxer regulations are *always* better for the diffusion of clean technologies than more stringent ones, nor that environmental R&D subsidies could harm environmental innovation. Such subsidies should naturally be expected

[8] See e.g., Requate and Unold (2003) and Perino (2010).

[9] This is a common assumption found for example in Milliman and Prince (1989), Laffont and Tirole (1996), Fischer et al. (2003) to name a few.

to foster the development of more efficient environmental innovations, thus facilitating their diffusion.[10] Nevertheless, since the clean technology industry is marked by a high degree of concentration, which enables private firms to exert some market power when licensing their technologies, further public intervention at the diffusion stage might be needed to ensure that these technologies will be adequately disseminated. This paper's only goal is to point at possibility results, which to date have been overlooked by the literature.

## 1.1 Related literature

Broadly considered, the process of induced environmental innovation (by which technological innovation is connected to environmental regulation) has sparked a wide body of theoretical and empirical literature (see e.g., Popp et al. (2009) for an overview of this literature). Thus far, much emphasis has been placed on the impact that the *design* of environmental regulation (e.g., the regulatory instrument choice, the regulation stringency or time consistency) might have on its so-called *dynamic efficiency*.[11] By contrast, the influence that strategic interactions among polluters might have on a technology supplier's incentives to disseminate patented clean technologies has received only limited attention.

Among the few papers emphasizing the strategic role of investment in environmental R&D in oligopoly, the closest in spirit to the present paper are Montero (2002) and Montero (2003) both of which examine the impact of environmental regulation on polluters' incentives to invest in environmental R&D before engaging in imperfect competition. There as well, however, the extent of strategic interaction might be artificially limited for at least two reasons. Firstly, the author focuses on end-of-pipe abatement so that in Montero (2003) "Under tax regulation there is no strategic effect because [a firm's] R&D investments do not affect its marginal production costs..., and consequently, its output." Secondly, but perhaps more importantly, in both papers the analysis is mostly restricted to *symmetric* investment decisions. Yet, as we argue below, even when polluters are symmetric at the outset, *asymmetric* investment patterns might arise in equilibrium.

That ex ante identical firms might take different investment decisions and eventually end up implementing distinct technologies, however, is not specific to our model. For instance, in Requate and Unold (2003), where identical polluters are subject to a pollution permits system, some could find it optimal to adopt the advanced abatement technology, while some others might find it optimal not to do so. However, since these authors consider a perfectly competitive

[10] See e.g., David and Sinclair-Desgagné (2010).

[11] That is, on its efficiency in inducing the development and the diffusion of clean technologies. For a survey of theoretical literature on the dynamic efficiency see Requate (2005a).

polluting industry, the reason they reach an asymmetric adoption equilibrium is very different from that underlying our results. In fact, under tax regulation, if a polluter, in their model, finds it profitable to adopt the advanced abatement technology, so should all the polluters. By contrast, under a permits system, it might be optimal to some polluters not to bear the costs of adopting the advanced abatement technology, but instead to free-ride on lower permit prices resulting from the adopters' abatement efforts.

Given that, in most models, a more stringent environmental regulation would result in more environmental innovation, more adoption of clean technology or more provision of abatement services, one might be tempted to conclude the existence of a monotone relationship between the stringency of environmental regulation and the diffusion of environmental innovations, so that, indeed, stricter regulations necessarily induce more diffusion of clean technology. Recently, however, Bréchet and Meunier (2012) and Perino and Requate (2012) have independently come to the similar conclusion that this need not be the case. Yet, since in both papers the authors consider a continuum of polluting firms, unlike our findings the non-monotonicity results reported therein, are not due to strategic interactions.

Finally, when analyzing the licensing of clean technologies, we build upon a generic literature on contracting with externalities, in which the licensing of cost-reducing innovations in oligopoly is a well-studied application to industrial organization (see e.g., **?** and Katz and Shapiro (1986)).[12]

### 1.2 Outline

The remainder of the paper is organized as follows. The next section presents the model. Section 3 derives the value of clean technology in a Cournot oligopoly. Section 4 show how the polluters' clean technology adoption individual decisions depend on the strategic interactions in their product market. Section 5 illustrates the induced diffusion of clean technology when the polluters face a linear demand curve. Section 6 provides further qualifications of our results and offers some concluding remarks. All proofs are relegated to the appendices.

## 2 The Model

Consider $n$ firms competing à la Cournot in a homogenous product market and facing a downward-sloping inverse demand given by $P(Q)$ where $Q$ denotes the industry aggregate output (i.e.

[12]See Segal (1999) and the reference therein or Sen and Tauman (2007) for a survey devoted to cost-reducing innovations.

$P'(Q) < 0$ for all $Q > 0$). Suppose that, *initially*, all firms use a conventional constant return-to-scale technology which generates pollution as byproduct emissions of a regulated pollutant, and let us refer to these firms as *the polluters*. The (constant) marginal cost of the conventional production process is normalized to zero and its *emission rate*, that is, the emissions to output ratio, is normalized to the unity. Suppose that the polluters are subject to an emissions tax policy and let $\tau$ denote the tax rate to be levied on each pollution unit emitted during the (forthcoming) compliance period. Thus, when producing $q$ units of output, absent the emission tax, a *conventional polluter* would generate $q$ units of emissions while incurring no production costs. However, because of the emission tax policy, that polluter would actually perceive a total cost $qt$.

Then, suppose the existence of a patented innovation altering the polluters' production process in a way that reduces the emission rate from 1 to $(1 - \alpha)$ with $\alpha \in (0, 1]$. Since this technology is patented, a polluter must acquire a license to incorporate it into its production process. Following previous literature, we assume for simplicity that the *technology supplier* belongs to a separate unregulated industry and that there are no other alternative clean technologies.[13] In other words, our *technology supplier* is an unconstrained monopolist able to optimally control the extent of diffusion of its technology and to appropriate the corresponding share of the environmental rents accruing to the licensees.[14]

Let us assume that, while lowering the emission rate, *the clean technology* $\alpha$ might, however, entail a larger unit production cost $c$ with $c \geq 0$. Thus, absent the emissions tax, when producing $q$ units of output, a *licensee* implementing the clean technology $\alpha$ would generate $(1 - \alpha)q$ units of emissions while incurring a total production cost $cq$. However, because of the emissions tax policy, that polluter would perceive a total cost $(c + (1 - \alpha)t)q$. Hence, given the emissions tax rate, the parameters $\alpha$ and $c$ capture the *perceived* efficiency of the clean technology $\alpha$. The former captures the environmental efficiency (the higher $\alpha$, the cleaner is the technology) while the latter represents its cost efficiency.

To sum up, each polluter perceives a (constant) marginal cost encompassing the production unit cost and the *marginal compliance cost* associated with the emission rate of its production process (i.e. $0 + \tau$ for a conventional polluter and $c + (1 - \alpha)t$ for a licensee). The polluters' adoption and production decisions will actually be based on those perceived costs. As shown in Figure 1 the perceived "merit order" of both technologies depends on the emissions tax rate $t$. When the emission tax is sufficiently high (i.e. $t > \underline{t}$), the clean technology $\alpha$ is perceived as

[13] See e.g., Laffont and Tirole (1996), Requate (2005a), Montero (2011).

[14] Arguably, the technology supplier's pricing behavior could be constrained by various factors, such as the threat of imitation around its patents. See e.g., Fischer et al. (2003).

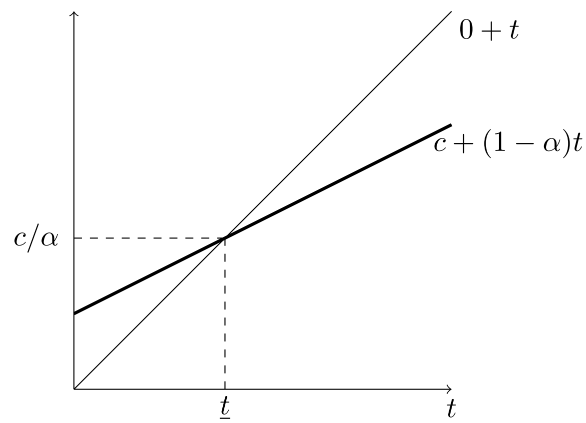


Figure 1: Perceived unit costs as a function of $t$

more efficient than the conventional one, while the opposite holds when the tax is too low (i.e. $t < \underline{t}$). At this point, it is worth mentioning that, throughout, the parameters $t$, $\alpha$ and $c$ are all treated as being exogenously given. In our comparative statics analysis, we focus only on $t$ and $\alpha$, which are the most relevant for our purpose.

We shall analyze the following game. Based on emissions tax rate $t$, the technology supplier decides on the extent to which the clean technology $\alpha$ will be disseminated through licensing (e.g., by setting a fixed license fee accordingly), thereby determining the industry technological structure. The licensees pay their licensing fees and the polluters simultaneously take their production decisions. At the end of the compliance period, each polluter receives its Cournot profit and proceeds to the payment of emissions taxes (if any). We solve this game for a subgame perfect Nash equilibrium consisting of the number of licenses that maximizes the technology supplier's licensing revenues.

**Notations.** For further reference, let $q^{\emptyset}$, $e^{\emptyset}$ and $\pi^{\emptyset}$ respectively denote the equilibrium output, the corresponding emissions level and profit of each firm in the *laissez-faire* regime, that is, absent any environmental regulation. For a given emissions tax rate $t$ and $\gamma \in \{0, \alpha\}$, let $q_\gamma(k, \alpha, t)$, $e_\gamma(k, \alpha, t) = (1-\gamma)q_\gamma(k, \alpha, t)$ and $\pi_\gamma(k, \alpha, t)$ denote respectively the equilibrium output, the corresponding emissions level and profit of a firm operating with technology $\gamma$ conditional on $k$ firm(s) having adopted the technology $\alpha$. Moreover, let $Q(k, \alpha, t)$ and $E(k, \alpha, t)$ denote the corresponding equilibrium aggregate output and emissions level, respectively.

# 3 The value of clean technology in Cournot oligopoly

We assume (merely for technical reasons) that $P(Q)$ is twice continuously differentiable and satisfies the following assumption.[15]

**Assumption 1** ***(A1)*** *$\Theta(Q) \equiv P''(Q)Q/P'(Q) > -2$ for all $Q > 0$.*

Next, let us define the two particular tax levels $\underline{t}(\alpha) \doteq c/\alpha$ and $\hat{t} \doteq \min\{t : \text{such that} \quad q_0(n-1, 1, \hat{t}) = 0\}$. Throughout, we assume that the environmental regulation is neither too lax nor too stringent in that the following assumption holds.

**Assumption 2** ***(A2)*** *$\underline{t}(\alpha) < t < \hat{t}$*

This assumption will allow us to focus on interior equilibria of the product market subgame. Indeed, notice that the worst situation for a conventional polluter faced with a given emission tax level $t$ is when all of its product market competitors are operating with the cleanest technology (i.e. when $k = n-1$ and $\alpha = 1$). Hence, as long as the emission tax level is such that even in such a situation the former would continue to produce a strictly positive quantity in equilibrium, Assumption 2 ensures that in equilibrium each firm produces a strictly positive quantity regardless of the industry technological structure (i.e. for all $k$ and all $\alpha$).

## 3.1 Product market equilibrium with $k$ licensees

Now, suppose that $k$ licensees implement the clean technology $\alpha$, while $n-k$ polluters still use the conventional technology. Given the emission tax level, $t$, each licensee would perceive the constant marginal cost $c+(1-\alpha)t$, while each of the $n-k$ conventional polluters would perceive the constant marginal cost $t$ (recall that each unit of output generates one unit of emissions). Thus, taking as given the outputs $Q_{-q}(\alpha, k, t)$ of its competitors, each licensee would solve

$$\max_q \pi_\alpha(q|k,t) = [P(Q_{-q}(\alpha,k,t)) - c - (1-\alpha)t]q,$$

while each conventional polluter would solve

$$\max_q \pi_0(q|k,t) = [P(Q_{-q}(\alpha,k,t)) - t]q$$

Standard calculations then yield the following lemma.

[15] This assumption requires only that the demand function be not too concave and ensures the existence and uniqueness of a Cournot equilibrium in an asymmetric oligopoly. See for instance Février and Linnemer (2004) from which we borrow the notation $\Theta(Q)$.

**Lemma 1** *Under Assumptions (A1) and (A2), the aggregate equilibrium output $Q(k, \alpha, t)$ obtains as the solution in $Q$ to the following (aggregate) first-order condition:*

$$P'(Q)Q + nP(Q) = nt - k(\alpha t - c) \tag{1}$$

*The equilibrium output of each firm operating with the technology $\alpha$ is given by*

$$q_\alpha(k, \alpha, t) = \frac{Q}{n} + \frac{(n-k)(\alpha t - c)}{-nP'(Q)} \tag{2}$$

*whereas the equilibrium output of each firm operating with the conventional technology is given by*

$$q_0(k, \alpha, t) = \frac{Q}{n} - \frac{k(\alpha t - c)}{-nP'(Q)} \tag{3}$$

*For $\gamma \in \{0, \alpha\}$, the equilibrium profit of a polluter implementing the technology $\gamma$ is given by*

$$\pi_\gamma(k, \alpha, t) = -P'(Q)q_\gamma^2(k, \alpha, t) \tag{4}$$

**Proof.** See Appendix. ■

In fact, the equilibrium outcomes in the polluting industry would be those of a n-firm Cournot oligopoly with $n-k$ firms operating at a perceived marginal cost $c+t$ and $k$ firms operating at a perceived marginal cost $c+(1-\alpha)t$. From these equilibrium outcomes we can derive the following proposition.

**Lemma 2** ***(The impact of technological innovation on polluters' individual profits)*** *Suppose Assumptions (A1) and (A2) hold. Then:*

1. *For all $k \in \{1, 2..., n-1\}$ we have $\frac{\partial \pi_\alpha(k,\alpha,t)}{\partial k} < \frac{\partial \pi_0(k,\alpha,t)}{\partial k} < 0$ .*
2. *For all $\alpha \in (0,1)$ we have $\frac{\partial \pi_0(k,\alpha,t)}{\partial \alpha} < 0 < \frac{\partial \pi_\alpha(k,\alpha,t)}{\partial \alpha}$.*

**Proof.** See Appendix. ■

Observe first that given the technology efficiency and emissions tax level, every additional license sold by the technology supplier deprives each of its licensees of some competitive advantage, since this means sharing the perceived cost-leadership with a larger number of equally efficient rivals. Although this also places conventional polluters at a greater competitive disadvantage, assertion (i) indicates that the adverse effect of an additional license on individual profits is greater for a licensee than for a conventional polluter. Moreover, *ceteris paribus*, from the licensees' standpoint an increase in the clean technology environmental efficiency amounts to a greater perceived cost-advantage over conventional competitors and thus results in increased individual profits. On the contrary, from the latter's standpoint such an increase results in a higher cost-disadvantage and thus in reduced individual profits.

### 3.2 Compliance cost savings and environmental rents

When the clean technology $\alpha$ is implemented by $0 < k \leq n$ licensees, the polluting industry is potentially composed of two types of polluters: $n-k$ conventional ones and $k$ licensees. For each polluter, the cost of complying with the emissions tax $t$ is given by the difference between the profit it would have gained had the regulation not been enforced (i.e. under *laissez-faire*) and that actually realized at the end of the compliance period. That is, for a polluter implementing the technology $\gamma \in \{0, \alpha\}$, these compliance costs are given by $\pi^{\emptyset} - \pi_{\gamma}(k, \alpha, t)$. Therefore, the individual costs of complying with a given environmental policy and, hence, the individual compliance cost savings allowed by the adoption of the clean technology depend on the industry technological structure.

Suppose for instance that the technology $\alpha$ has been licensed to $k-1$ polluters. By acquiring a license, a conventional polluter would save on compliance costs an amount given by

$$\delta(k, \alpha, t) = \pi_{\alpha}(k, \alpha, t) - \pi_0(k-1, \alpha, t)$$

Thus, as mentioned above, because of strategic interactions in their product market, the compliance cost savings resulting from the adoption technology $\alpha$ depend not only on the environmental regulation stringency (i.e the emission tax level $t$), but also on the industry technological structure.

Now, consider the following difference which we refer to as the individual *environmental rents* from technological innovation:

$$\Delta(k, \alpha, t) \equiv \begin{cases} \pi_{\alpha}(k, \alpha, t) - \pi_0(k, \alpha, t) & \text{if} \quad k < n \\ \delta(n, \alpha, t) & \text{otherwise.} \end{cases}$$

Observe that when the industry is subject to an emissions tax $t$, $\Delta(k, \alpha, t)$ measures the (gross) gains from implementing the clean technology $\alpha$ when there are $k$ licensees.[16] Moreover, notice that the individual environmental rents can be decomposed as follows.

$$\Delta(k, \alpha, t) = \underbrace{\pi_{\alpha}(k, \alpha, t) - \pi_0(k-1, \alpha, t)}_{\delta(k,\alpha,t)} - \underbrace{[\pi_0(k, \alpha, t) - \pi_0(k-1, \alpha, t)]}_{\lambda_0(k,\alpha,t)} \tag{5}$$

As we have seen above, in our Cournot settings the term $\lambda_0(k, \alpha, t)$ is negative, which suggests

[16]For instance, if the $k$ licenses were auctioned by the technology supplier, any polluter would bid more than , $\Delta(k, \alpha, t)$. See e.g.,Katz and Shapiro (1986).

that whenever the number of licensees is strictly lower than the number of polluters, the gross private gains from implementing the clean technology exceed the mere individual compliance cost savings resulting from its adoption (i.e. for all $k < n$, $\Delta(k, \alpha, t) > \delta(k, \alpha, t)$). The next lemma indicates how technological innovation affects the polluters' profits for a given emissions tax rate.

**Lemma 3** ***(Polluters' willingness to pay for clean technology)***
*Suppose Assumptions 1 and 2 hold. Then:*

1. *For all* $k \in \{1, 2..., n-1\}$ *we have* $\frac{\partial \Delta(k,\alpha,t)}{\partial k} < 0$.
2. *For all* $\alpha \in (0, 1)$ *we have* $\frac{\partial \Delta(k,\alpha,t)}{\partial \alpha} > 0$.

**Proof.** Follows immediately from Lemma 2. ■

Lemma 3 can be regarded as a corollary of Lemma 2. Indeed, as the latter indicates, the profit forgone by a licensee when the technology supplier sells an additional license is greater than that forgone by a conventional polluter. As a result, the opportunity cost of acquiring a license increases as the number of licensees increases, thereby suppressing each conventional polluter's willingness to pay for implementing the clean technology $\alpha$. Besides, more intuitively, given the number of licensees and the emissions tax rate, the more efficient the clean technology, the greater the individual environmental rents from implementing it, and thus, the more each polluter is ready to pay for a license.

**Lemma 4** ***(The effect of increasing the emissions tax)***
*Suppose Assumptions 1 and 2 hold. Then: For all* $t \in (\underline{t}(\alpha), \hat{t})$ *we have* $\frac{\partial \Delta(k,\alpha,t)}{\partial t} > 0$.

**Proof.** See Appendix. ■

As one could expect, for a given number of licensees and given the technology efficiency, the higher is the emissions tax rate, the greater are the individual environmental rents arising from implementing the clean technology $\alpha$ and thus the higher the individual willingness to pay for a license to use that technology.

# 4 Strategic adoption of clean technology

Let us now turn to the equilibrium in the diffusion subgame. We first give the following lemma.

**Lemma 5** *Given emissions tax rate* $t$*, if the license fee* $F$ *is such that* $\Delta(k, \alpha, t) \geq F > \Delta(k + 1, \alpha, t)$*, then, in equilibrium, at most* $k$ *polluters implement the clean technology* $\alpha$.

**Proof.** See Appendix. ■

Note that throughout, as in Fischer et al. (2003), Laffont and Tirole (1996), Montero (2011) and Requate (2005b), we assume that the costs of adopting the clean technology $\alpha$ simply consist in the license fee $F$. Otherwise, $F$ should be understood as the total adoption costs.

**Proposition 1** ***(Induced demand for clean technology)***

1. *Given the emission tax $t$, there exists a threshold $\underline{F}(\alpha, t) > 0$ (resp. $\bar{F}(\alpha, t)$) such that for all $F < \underline{F}(\alpha, t)$ (resp. $F > \bar{F}(\alpha, t)$) complete diffusion (resp. no diffusion) is the unique equilibrium outcome of the diffusion subgame.*
2. *For all $F$ such that $\underline{F} < F < \bar{F}$ there exists a unique equilibrium number $k(F, \alpha, t)$ of firm(s) adopting the clean technology $\alpha$.*
3. *Moreover, $k(F, \alpha, t)$ is a weakly decreasing in $F$, weakly increasing in $\alpha$ and weakly increasing in $t$.*

**Proof.** See Appendix ■

The first two assertions follow from Lemma 5 and Lemma 3. Indeed, no polluter would switch to the patented technology were the license fee to exceed the resulting benefits from implementing the clean technology $\alpha$. Likewise, all polluters would adopt that technology were the resulting individual compliance cost savings to offset the license fee. For intermediate values of the license fee, it privately optimal to some polluters no to acquire a license. Naturally, for a given license fee, an increase in the regulation stringency or in the environmental efficiency of the clean technology strengthens the demand for the clean technology. However, given the emissions tax rate, the higher the license fee charged by the technology supplier for the technology $\alpha$, the lower the number of polluters actually buying a license.

## 4.1 Discussion

Proposition 1 contrasts with the "all or none" results from the received literature on abatement technology adoption where strategic interactions in the downstream market are not considered. For instance, note that in Milliman and Prince (1989), Fischer et al. (2003) or Requate and Unold (2003), if when faced with an emission tax a polluter finds it profitable to adopt an advanced abatement technology, so should all the polluters. Thus, given the adoption costs, either all or none of the polluters will implement the environmentally sounder technology. In other words, in this case, the induced demand for abatement technologies does not depend at all on strategic interactions among the polluters. In our framework, despite the *ex ante* symmetry, from the polluters' perspective it might be optimal to implement distinct technologies in equilibrium. This is in line with the findings of Bréchet and Meunier (2012) who derive asymmetric equilibrium adoption in a model where price-taking polluters supply a competitive output market, the price of which is endogenously determined. However, in their model incomplete diffusion might be socially optimal because the polluting firms incur some sunk adoption costs as in Requate and Unold (2003). Instead, we are considering efficient clean technologies for which complete diffusion would be socially desirable. Yet, whether complete diffusion of a patented technology occurs or not in equilibrium ultimately depends on the technology supplier's willingness to disseminate that technology. This, in turn, depends on the impact of its diffusion on licensing revenues.

# 5 Privately optimal dissemination of clean technology

We now turn to the technology supplier's licensing revenue maximization problem. To facilitate closed-form solutions, we further assume that the polluters face a linear demand curve.

**Assumption 3** *(A3)* $P(Q) = a - bQ$*, with* $a > 0$ *and* $b > 0$*.*

Assumption 1 holds trivially for linear demand functions for which $\Theta(Q) = 0$ for all $Q > 0$. Assumption 2, in turn, can be more readily expressed as

**Assumption 4** *(A4)* $c/\alpha < t < \hat{t} \doteq (a - c)/n$*.*

We are thus able to investigate how the structural parameters of the polluters' product market affect the number of licenses sold in equilibrium in the diffusion subgame. First, observe that for a given license fee $F$, the technology supplier's licensing revenue can be written as

$$\Pi(F, \alpha, t) = k(F, \alpha, t)F$$

where $k(F, \alpha, t)$ is the equilibrium number of licensees as defined in Proposition 1. Let $F^*(\alpha, t)$ and $k^*(\alpha, t)$ denote respectively the revenue maximizing license fee and and the corresponding equilibrium number of licensees. The following proposition then indicates how the polluters' market structural parameters affect the technology supplier's dissemination incentives.

**Proposition 2** *Suppose Assumptions (A3) and (A4) hold, then :*

1. *For given* $a$*,* $n$ *and* $\alpha$*, we have* $\partial F^*(\alpha, t)/\partial t \geq 0$ *and hence* $\partial k^*(\alpha, t)/\partial t \leq 0$*,*
2. *For given* $a$*,* $n$ *and* $t$*, we have* $\partial F^*(\alpha, t)/\partial \alpha \geq 0$ *and hence* $\partial k^*(\alpha, t)/\partial \alpha \leq 0$*,*
3. *For given* $\alpha$*,* $n$ *and* $t$*, we have* $\partial F^*(\alpha, t)/\partial a \leq 0$ *and hence* $\partial k^*(\alpha, t)/\partial a \geq 0$*,*
4. *For given* $a$*,* $\alpha$ *and* $t$*, we have* $\partial F^*(\alpha, t)/\partial n \leq 0$ *and hence* $\partial k^*(\alpha, t)/\partial n \geq 0$

**Proof.** See Appendix ■

As the proposition indicates, contrary to conventional wisdom stricter environmental regulation (i.e. a higher emissions tax) need not induce more widespread diffusion of clean technology (1). Moreover, given the regulation stringency, more effective clean technologies could well be implemented by fewer polluters than would have been less effective ones (2). These counter-intuitive results could be explained as follows: when setting its license fee, the technology supplier trades off two countervailing effects. On the one hand, selling an extra license at a given price increases revenue (*the revenue effect*), but on the other hand, each licensee imposes a negative externality (reduced profits) on all other polluters and thus reduces their willingness to pay for a license (*the rent dissipation effect*). Thus, since the equilibrium number of licensees ultimately depends on the license fee set by the technology supplier, whether or not complete diffusion occurs in equilibrium depends on whether the revenue effect dominates the rent dissipation effect, which in turn depends on the polluters' market structural parameters.

In words, Proposition 2 says that *ceteris paribus* (3) the technology supplier's optimal number of licenses weakly increases with the of the polluters' market size, as captured by the parameter $a$ and (4) weakly increases with the number $n$ of polluters. Note that in our framework with *ex ante* symmetric firms, the number of polluters also captures the market concentration in the polluting industry. Thus, the more competitive the polluters' output market, the weaker the rent dissipation effect relative to the revenue effect. In fine, whether *rationing*, that is, precluding some polluters from adopting a given clean technology, is privately optimal to the technology supplier depends on the polluting industry structural parameters (e.g., number of firms, demand elasticity, *et cetera*).

**Proposition 3** *Define* $\underline{t}(\alpha)$ *such that* $k^*(\alpha, \underline{t}(\alpha)) = n-1$*, then for all* $t \in (\underline{t}(\alpha), \hat{t})$*, it is optimal for the technology supplier to partially disseminate the technology* $\alpha$ *(i.e. to ration the polluters) if and only if* $\alpha \geq \bar{\alpha} \doteq \frac{2(n-1)}{3n-5}$.

**Proof.** See Appendix. ■

In fact, as Proposition 3 shows, rationing is privately optimal from the technology supplier's standpoint, and therefore incomplete diffusion occurs in equilibrium only whenever two conditions are simultaneously met: the clean technology $\alpha$ must be sufficiently effective (i.e. $\alpha > \bar{\alpha}$) and the regulation must be sufficiently stringent (i.e. $t > \bar{t}(\alpha)$). Whenever one of these conditions is not fulfilled, the revenue effect dominates the rent dissipation effect and it is privately optimal for the technology supplier to fully disseminate the clean technology and therefore, complete diffusion occurs in equilibrium. For instance, when the clean technology is not efficient enough (i.e. $\alpha < \bar{\alpha}$) the revenue effect always dominates the rent dissipation effect and any admissible level of regulation stringency leads to complete diffusion of the clean technology. When the clean technology is more efficient (i.e. $\alpha > \bar{\alpha}$), there exist some admissible levels of regulation stringency (all $t > \bar{t}(\alpha)$) that make the rent dissipation effect sufficiently strong to induce the technology supplier to ration the polluters by setting a license fee such that at least one of them finds it profitable not to acquire a license.

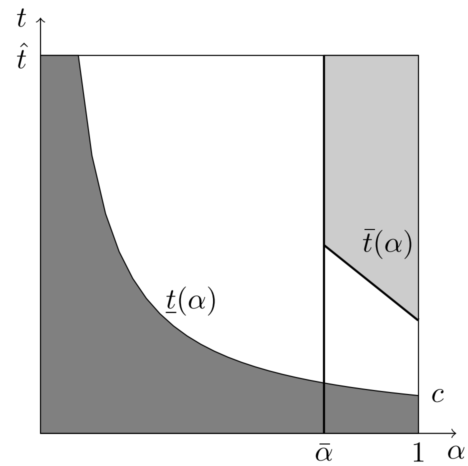


Figure 2: Equilibrium diffusion: All combinations $(\alpha, t)$ in the dark grey (resp. white) area lead to no (resp. complete) diffusion, while all combinations $(\alpha, t)$ in the grey area lead to rationing.

## 6 Concluding Remarks

Conventional wisdom usually associates more stringent regulation with more diffusion of clean technology. In this paper, we have investigated the impact of environmental regulation stringency on the diffusion of patented clean technologies when the polluters compete in an oligopolistic industry. We have shown that, in general, each polluter's willingness to pay for clean technology and thereby, the innovator's incentives to disseminate such technologies, depend not only on both the environmental regulation stringency and the technological efficiency, but also on the strategic interactions between the potential licensees shaping the rents that the technology supplier (the technology supplier) can extract from each of its licensees. Moreover, focusing on emissions taxation within Cournot oligopoly, we have seen that, from the technology supplier's standpoint, preventing some polluters from obtaining a license is privately optimal only whenever two conditions are simultaneously met: the patented clean technology must be efficient enough and the environmental regulation must be stringent enough. Therefore, contrary to conventional wisdom, more stringent regulations need not result in more diffusion of clean technology. Our results, however, call for further qualifications.

**Exclusive technology licensing.** The extent to which a private technology supplier can extract from its licensees depends (among other things) on the contracting environment in which licensing occurs. For the rent dissipation effect to ever play a role, exclusive licensing contracts must be enforceable, which is often the case in the context of clean technologies.[17]

**Competing clean technologies.** In our model (as in all the aforementioned papers), the "outside option" of potential licensees is to keep their current technology. Hence, the technology supplier is endowed with *unconstrained* monopoly power over the use of its technology. Although common in the literature (see e.g., Laffont and Tirole (1996) and Fischer et al. (2003) and Montero (2011)), this assumption extremely simplifies the complex structure of the clean technology industry. Competition in this industry can be expected to help discipline technology suppliers and drive the license fees down (thereby mitigating the rent dissipation effect). However, the argument developed above can be extended to the case of competing clean technologies as follows. Suppose another *inferior* clean technology $\beta$ exists with $0 < \beta < \alpha < 1$, (i.e another outside option) and define $\pi_\beta(k, \alpha, t)$, the profit of a polluter using technology $\beta$ when $k$ polluters use technology $\alpha$ while $n - k$ polluters use technology $\beta$

$$\Delta_\alpha(k, \beta, t) = \pi_\alpha(k, \alpha, t) - \pi_\beta(k, \alpha, t)$$

The technology supplier would then solve

$$\max_k LR_\alpha(k, \alpha, t) = k\Delta_\alpha(k, \alpha, t)$$

Therefore, if $\beta << \alpha$ the same two effects are still at play.

[17]For example, business media often advertise licensing agreements of this sort :

> Clean Coal Technologies, Inc. (OTCQB: CCTC) (PINK: CCTC), an emerging cleaner-energy company utilizing patented technology to convert raw coal into a cleaner-burning, more efficient fuel, has announced the execution of a Joint Venture Agreement with Archean Group, as well as an exclusive Technology Licensing Agreement for the ASEAN region with Good Coal PTE., Ltd. ("Good Coal").

# Appendix

## Proof of Lemma 1

When the technology $\alpha$ is implemented by $k$ licensees, the first-order condition for a firm operating with the technology $\gamma \in \{0, \alpha\}$ can be written as

$$P'(Q)q_\gamma(k, \alpha, t) + P(Q) = \frac{\gamma}{\alpha}c + (1 - \gamma)t \tag{6}$$

where omitting arguments, $Q$ denote the equilibrium equilibrium aggregate output. Summing over the $n$ first-order conditions gives equation (1). Hence, the solution in $Q$ to equation (1) is the equilibrium aggregate output. Moreover, taking $\gamma = \alpha$ in equation (6) and subtracting it from equation (1) gives expression (2) after rearranging terms. Similarly, taking $\gamma = 0$ in equation (6) and subtracting it from equation (1) gives expression (3). The expression for the profits (4) are derived from the F.O.C given in (1).

# Comparative statics on $Q(k, \alpha, t)$

For future reference we prove the following comparative statics results.

**1.** Totally differentiating equation(1) w.r.t $k$ yields

$$P'(Q)\frac{\partial Q(k, \alpha, t)}{\partial k}\left[\frac{P''(Q)Q}{P'(Q)} + n + 1\right] = -(\alpha t - c)$$

rearranging gives

$$\frac{\partial Q(k, \alpha, t)}{\partial k} = \frac{-(\alpha t - c)}{(\Theta + n + 1)P'(Q)} > 0. \tag{7}$$

for all $k < n$.

**2.** Proceeding analogously we obtain

$$\frac{\partial Q(k, \alpha, t)}{\partial \alpha} = \frac{-kt}{(\Theta + n + 1)P'(Q)} > 0 \tag{8}$$

for all $\alpha < 1$.

**3.** Proceeding analogously we obtain

$$\frac{\partial Q(k, \alpha, t)}{\partial t} = \frac{n - k\alpha}{(\Theta + n + 1)P'(Q)} \leq 0 \tag{9}$$

with equality if $k = n$ and $\alpha = 1$.

## Proof of Lemma 2

Let $s_\gamma = s_\gamma(k,\alpha,t) \equiv q_\gamma(k,\alpha,t)/Q(k,\alpha,t)$ denote the equilibrium market share of a firm operating with the technology $\gamma \in \{0,\alpha\}$ when the technology $\alpha$ is implemented by $k$ licensees.

**1.** Observe first that the equilibrium profit of a firm operating with the technology $\gamma$ can be written as

$$\pi_\gamma(k,\alpha,t) = -P'(Q(k,\alpha,t))q_\gamma^2(k,\alpha,t) \tag{10}$$

Then, totally differentiating equation (10) w.r.t $k$ yields

$$\frac{\partial \pi_\gamma(k,\alpha,t)}{\partial k} = -2P'(Q)\frac{\partial q_\gamma}{\partial k}q_\gamma - \frac{\partial Q}{\partial k}P''(Q)q_\gamma^2$$

which, after making use of expression (7) and rearranging terms can be written as

$$\frac{\partial \pi_\gamma(k,\alpha,t)}{\partial k} = -q_\gamma\left[2P'(Q)\frac{\partial q_\gamma}{\partial k} - \frac{\alpha t - c}{\Theta+n+1}\Theta s_\gamma\right] \tag{11}$$

Totally differentiating equation (6) w.r.t $k$ and rearranging terms yields

$$P'(Q)\frac{\partial q_\gamma}{\partial k} = (\alpha t - c)\left[\frac{\Theta s_\gamma + 1}{\Theta+n+1}\right] \tag{12}$$

Using equation (12) and manipulating equation (11) we obtain

$$\frac{\partial \pi_\gamma(k,\alpha,t)}{\partial k} = -(\alpha t - c)q_\gamma\left[\frac{\Theta s_\gamma + 2}{\Theta+n+1}\right] < 0 \tag{13}$$

where the inequality follows from Assumptions (A1) and (A2).

It remains to show that for $k < n$, we have $\frac{\partial \pi_\alpha(k,\alpha,\tau)}{\partial k} < \frac{\partial \pi_0(k,\alpha,\tau)}{\partial k}$, which is equivalent to show that $\frac{\partial \Delta(k,\alpha,\tau)}{\partial k} \equiv \frac{\partial \pi_\alpha(k,\alpha,\tau)}{\partial k} - \frac{\partial \pi_0(k,\alpha,\tau)}{\partial k} < 0$. Notice first that $\frac{\partial \Delta(k,\alpha,\tau)}{\partial k} = -\frac{(\alpha t-c)Q}{\Theta+n+1}\left[\Theta(s_\alpha+s_0)+2\right](s_\alpha - s_0)$ Then, from expressions (2) and (3) we have $s_\alpha - s_0 = -(\alpha t - c)/P'(Q)Q > 0$. Thus, we obtain

$$\frac{\partial \Delta(k,\alpha,\tau)}{\partial k} = P'(Q)\frac{(\alpha t - c)^2}{\Theta+n+1}\left[\Theta(s_\alpha+s_0)+2\right] < 0 \tag{14}$$

since Assumptions (A1) and (A2) ensure that $\Theta(s_\alpha + s_0) > -2$.

**2.** Totally differentiating equation (10) w.r.t $\alpha$, using expression (8) and rearranging terms yields

$$\frac{\partial \pi_\gamma(k,\alpha,\tau)}{\partial \alpha} = -q_\gamma\left[2P'(Q)\frac{\partial q_\gamma}{\partial \alpha} - \frac{kt}{\Theta+n+1}\Theta s_\gamma\right] \tag{15}$$

Then, taking $\gamma = \alpha$ and totally differentiating equation (6) w.r.t $\alpha$ yields and making use of expression (8) yields, after some manipulations

$$P'(Q)\frac{\partial q_\alpha}{\partial \alpha} = -\tau\left[\frac{\Theta(1-ks_\alpha)+n+1-k}{\Theta+n+1}\right] \tag{16}$$

Then, using equation (16) in expression (15) and rearranging terms we obtain

$$\frac{\partial \pi_\alpha(k,\alpha,\tau)}{\partial \alpha} = -q_\alpha \tau \left[ \frac{\Theta(3ks_\alpha - 2) + 2(n-k+1)}{\Theta + n + 1} \right] > 0 \tag{17}$$

Likewise, taking $\gamma = 0$ and totally differentiating equation (6) w.r.t $\alpha$ yields after some manipulations

$$P'(Q)\frac{\partial q_0}{\partial \alpha} = kt \left[ \frac{\Theta s_0 + 1}{\Theta + n + 1} \right] < 0 \tag{18}$$

and using equation (18) in expression (15) and rearranging terms we obtain

$$\frac{\partial \pi_0(k,\alpha,\tau)}{\partial \alpha} = -q_0 kt \left[ \frac{\Theta s_0 + 2}{\Theta + n + 1} \right] < 0 \tag{19}$$

## Proof of Lemma 4

Totally differentiating equation (10) w.r.t $\tau$, using expression (9) and rearranging terms yields

$$\frac{\partial \pi_\gamma(k,\alpha,\tau)}{\partial t} = -q_\gamma \left[ 2P'(Q)\frac{\partial q_\gamma}{\partial \alpha} + \frac{n-k\alpha}{\Theta + n + 1}\Theta s_\gamma \right] \tag{20}$$

Then, for $\gamma \in \{0, \alpha\}$, totally differentiating equation (6) w.r.t $\tau$ yields after simple manipulations

$$P'(Q)\frac{\partial q_\gamma}{\partial t} = (1-\gamma) - \frac{\Theta s_\gamma}{\Theta + n + 1}(n - k\alpha)$$

Next, taking $\gamma = \alpha$, using equation (6) in expression (20) and rearranging terms we obtain

$$\frac{\partial \pi_\alpha(k,\alpha,\tau)}{\partial t} = q_\alpha \left[ \frac{(\Theta s_\alpha + 2)(n-k\alpha)}{\Theta + n + 1} - 2(1-\alpha) \right] \tag{21}$$

and taking $\gamma = 0$, using equation (6) in expression (20) and rearranging terms we obtain

$$\frac{\partial \pi_0(k,\alpha,t)}{\partial t} = q_0 \left[ \frac{(\Theta s_0 + 2)(n-k\alpha)}{\Theta + n + 1} - 2 \right] \tag{22}$$

Hence, comparing expression (21) and (22), we see that $\frac{\partial \pi_\alpha(k,\alpha,t)}{\partial t} < 0 \implies \frac{\partial \pi_0(k,\alpha,t)}{\partial t} < 0$. However, it is possible that for some small value of $t$ we have $\frac{\partial \pi_0(k,\alpha,t)}{\partial t} < 0 < \frac{\partial \pi_\alpha(k,\alpha,t)}{\partial t}$ or even $0 < \frac{\partial \pi_0(k,\alpha,t)}{\partial t} < \frac{\partial \pi_\alpha(k,\alpha,t)}{\partial t}$.

## Proof of Proposition 1

**1.** Since $\frac{\partial \Delta(k,\alpha,t)}{\partial k} < 0$, using Lemma 5 it is clear that if $F < \underline{F}(\alpha,t) = \Delta(n,\alpha,t)$, then in equilibrium all the polluters should implement the clean technology $\alpha$. Likewise, if $F > \bar{F}(\alpha,t) = \Delta(1,\alpha,t)$, then in equilibrium no polluters should implement the clean technology $\alpha$.
**2.** For any given intermediate value of $\Delta(n,\alpha,t) < F < \Delta(1,\alpha,t)$, the strict monotonicity in $k$ of $\Delta(k,\alpha,t)$ implies that there only one number $k = k(F,\alpha,t)$, $0 < k < n$ such that

$\Delta(k,\alpha,t) < F < \Delta(k+1,\alpha,t)$.

**3.** The last assertion also follows from the strict monotonicity of $\Delta(k,\alpha,t)$.

## Proof of Proposition 2

First, observe since $\delta(k,\alpha,t)$ is the maximal rents that the technology supplier can extract from each of its $k$ licensees with a fixed fee, the technology supplier's profit-maximization problem is equivalent to the following problem

$$\max_{k\leq n} k\delta(k,\alpha,t) = k\left[\frac{2(a-c-t)+(n-2k+2)\alpha t}{b(1+n)^2}\right] \tag{23}$$

Solving (23) for $k$ yields

$$k(\alpha,t) = \min\{n, Int\left(\frac{2(a-c-t)+(n+2)\alpha t}{4\alpha t}\right)\} \tag{24}$$

where $Int\,(x)$ denote integer part of $x$ i.e the larger integer lower than $x$. Hence, as long as the optimal strategies are rationing, we have 1) $\partial k(\alpha,t)/\partial t = -2(a-c)/\alpha t^2 < 0$; 2) $\partial k(\alpha,t)/\partial\alpha = -(a-c-t)/2\alpha^2 t < 0$; 2) $\partial k(\alpha,t)/\partial a = 1/2\alpha t < 0$; and 4) $\partial k(\alpha,t)/\partial n = 1/4 > 0$.

## Proof of Proposition 3

For a given $t$, consider the following rationing conditions

$$\frac{2(a-c-t)+(n+2)}{4\alpha t} = n-1 \tag{25}$$

Solving equations (25) for $t$ yields the lower bounds on the emission tax rates that induce the technology supplier to use a licensing strategy precluding at least one firm from implementing the technology $\alpha$:

$$t^f(\alpha) = \frac{2(a-c)}{(5n-6)\alpha+2} \tag{26}$$

Then, solving $t(\alpha) = \hat{t}$ (where $\hat{t} \doteq (a-c)/n$ as defined in Assumption 4) for $\alpha$ and using assertions 3) and 4) of Proposition 3 yields the result.

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